

DiskFit: A CODE TO FIT SIMPLE NON-AXISYMMETRIC GALAXY MODELS EITHER TO PHOTOMETRIC IMAGES OR TO KINEMATIC MAPS

J. A. SELLWOOD

Department of Physics and Astronomy, Rutgers University,
 136 Frelinghuysen Road, Piscataway, NJ 08854, USA

AND

KRISTINE SPEKKENS

Department of Physics, Royal Military College of Canada,
 PO Box 17000, Station Forces Kingston, ON K7K 7B4, Canada

Posted September 25, 2015

ABSTRACT

This posting announces public availability of version 1.2 of the *DiskFit* software package developed by the authors, which may be used to fit simple non-axisymmetric models either to images or to velocity fields of disk galaxies. Here we give an outline of the capability of the code and provide the link to downloading executables, the source code, and a comprehensive on-line manual. We argue that in important respects the code is superior to *rotcur* for fitting kinematic maps and to *galfit* for fitting multi-component models to photometric images.

Subject headings: galaxies: kinematics and dynamics — galaxies: structure — galaxies: spiral — methods: numerical

1. INTRODUCTION

The code *DiskFit* may be used to fit simple non-axisymmetric models either to images or to velocity fields of disk galaxies. If the fit is successful, *DiskFit* provides quantitative estimates of the non-circular flow speeds and an estimate of the mean circular speed when run on velocity fields (Spekkens & Sellwood 2007; Sellwood & Zánmar Sánchez 2010), and fractions of the galaxy light in a bar, disk, and bulge when run on images (Reese *et al.* 2007; Kuzio de Naray *et al.* 2012).

The kinematic branch of the code differs fundamentally from the frequently-used *rotcur* algorithm (Begeman 1987) since the minimization fits a global model to the complete map, rather than separate tilted rings, and it is superior to *reswri* (Schoenmakers *et al.* 1997) because it does not employ the epicyclic approximation to fit departures from circular motion. The photometric branch of the code also differs fundamentally from popular algorithms such as *galfit* (Peng *et al.* 2010) in that it fits non-parametric disk and bar light profiles rather than specified functional forms. Furthermore, it is superior to all three algorithms because it is capable of providing statistically valid, but realistic, estimates of the uncertainties in the fit. Kuzio de Naray *et al.* (2012) illustrate the functionality of *DiskFit* on high-quality kinematic and photometric data for the nearby galaxy NGC 6503.

A single code is provided to fit both photometric images and kinematic maps because, for both applications, *DiskFit* employs the same basic minimization algorithm originally described in the Appendix of Barnes & Sellwood (2003). The first applications (Barnes & Sellwood 2003) were to fit axisymmetric models; the extension to non-circular flows was described by Spekkens & Sellwood (2007)¹ and by

Sellwood & Zánmar Sánchez (2010), while Reese *et al.* (2007) extended the code to include barred models when fitting photometric images.

Note that *DiskFit* does not fit photometry and kinematics simultaneously; the same code simply fits either type of data depending on the users choice of inputs. Of course, if the user makes separate fits to both types of data from the same galaxy, the fitted values will likely differ.

2. CAPABILITIES OF THE CODE

DiskFit minimizes a χ^2 estimate of the differences between a projected model and the data. The data can be either a 2D velocity map derived from Doppler shifts of spectral lines obtained using an IFU in the optical or aperture synthesis in the radio, or a photometric image. The user can supply a map of uncertainties in the data and a mask image to indicate only good pixels to be fitted.

2.1. Fitting an axisymmetric model

Aside from an optional simple warp in the outer parts, the model presented to the data is a flat disk with inclination, i , and position angle, ϕ_d , that are assumed to be the same at all radii. Furthermore, the position of the center, (x_c, y_c) and, for kinematic fits only, the systemic velocity, v_{sys} , are parameters fitted to the entire 2D data set. A simple axisymmetric model will therefore fit any or all these parameters to determine global estimates that best fit the data.

In addition, *DiskFit* estimates either the circular speed, for kinematic data, or the mean intensity for a photometric image, at a set of radii specified by the user. Model values at data points that lie between the specified radii are computed by linear interpolation. It is important to note that this implies the model is simply a tabulated set of values over a range of radii and has *no pre-specified functional profile*, such as an exponential disk, *etc.*

sellwood@physics.rutgers.edu
 Kristine.Spekkens@rmc.ca

¹ *DiskFit* is also an extension of the publicly-available *velfit* 2.0.

2.2. Uncertainties

Uncertainties in the parameters, and in the intensity or circular speed at each radius, are estimated by a bootstrap method. The residuals from a simple model are generally correlated at neighboring pixels, because the model ignores spirals and other sources of correlated turbulence. The bootstrap algorithms employed attempt to preserve these correlated residuals (see Spekkens & Sellwood 2007; Sellwood & Zánmar Sánchez 2010, for a fuller discussion), which lead to larger and more realistic estimates of the uncertainties in the model.

2.3. Non-axisymmetric models

The most powerful aspect of *DiskFit* is that it can include simple non-axisymmetric features into the model and fit for their parameters. The most useful capability is to fit for a bar, which is a bi-symmetric distortion having a fixed position angle that is, in general, not aligned with, or perpendicular to, the major axis of projection. *DiskFit* allows for an underlying axisymmetric model on which a non-axisymmetric feature having a fixed position angle in the disk plane is superposed, and returns an estimate of the angle of its principal axis to the disk major axis. A bar that is almost aligned with the major or minor axis of projection may require that the fit is smoothed (see §2.7), but the bar cannot be separated from the disk by this algorithm when the alignment is exact; note that in such a case, an axisymmetric fit will be no worse than that obtained by other algorithms.

For kinematic fits, the non-circular flows have two m -fold symmetric components ($m = 2$ for a bar): a radial part that is the mean flow away from and towards the model center, and an azimuthal part that is the departure above and below the mean streaming speed. Each component varies in azimuth in the disk plane as a $\cos(m\theta)$ or a $\sin(m\theta)$ function, respectively, with zero phase on the bar major axis. These additional velocities are fitted at the same radii as those used to tabulate the circular speed, although the user can specify that the distortion has a smaller radial extent than the entire disk. *DiskFit* does not impose any relation between the radial and azimuthal velocity distortions, which can be arbitrarily large compared with the mean circular speed – *i.e.* it is not restricted to a small amplitude distortion. If the distortions turn out to be small, Sellwood & Zánmar Sánchez (2010) give formulae that can relate the fitted velocity distortions to the ellipticity of the potential.

For photometric fits, the bar represents a light component that increases the fitted intensity above the axisymmetric mean along the bar major-axis, with a corresponding reduction along the bar minor axis. The bar light profile is again tabulated at the same radii as the mean axisymmetric light profile.

In principle, *DiskFit* can fit for distortions having other rotational symmetries, such as $m = 1$ (lopsided) or $m = 3$ (trefoil) distortions, although they could not be spiral in form as the algorithm restricts the non-axisymmetric component to having a fixed position angle in the disk plane at all radii.

Less usefully, *DiskFit* can also fit for axisymmetric radial flows. However, radial flow velocities would need to

be unrealistically large – at least a few percent of the circular speed – to be detectable. Axisymmetric flow speeds of this magnitude would indicate the galaxy is in a transitional state and that extensive rearrangement of the mass distribution is taking place on a dynamical time-scale.

2.4. Spiral distortions

The largest residuals in fitted models generally arise from spiral arms, which are non-circular flows in kinematic maps and coherent features in photometric images. *DiskFit* does not attempt to fit these distortions, and merely treats them as sources of error that are allowed for in the bootstraps.

The reason is that these features are hard to model. Unlike bars, which are strong, clearly bisymmetric, and long-lived, mild spiral distortions are transient and probably result from multiple, superposed modes having different pattern speeds, and rotational symmetries.

2.5. Warp fitting

DiskFit allows the model to be warped in a simple, parametric manner. The code assumes that the line of nodes of the warp is at a fixed position angle, the warp begins at a certain radius, and increases in amplitude as a quadratic function of radius to some maximum amplitude at the last measured point. Since the kinematic signature of a warp closely resembles that of an in-plane bar, *DiskFit* will not allow the user to select both options in the same fit.

2.6. Bulge fitting

Photometric images can be fitted with a disk, bar and bulge model if desired. *DiskFit* makes the (highly questionable) assumptions that the bulge is both axisymmetric and symmetric about the disk mid-plane, and has a flattening that is constant with radius. It also assumes the parametric form of a Sérsic profile for the bulge, and will fit, if desired for the Sérsic index, n , effective radius, R_e , central intensity, I_0 , and flattening ϵ_b . A very high spatial resolution image is generally required to fit for all these parameters, and it is usually safer to hold at least n fixed at some reasonable value.

The user of this capability should bear in mind that the fitted values provided by the code are meaningful only if the above listed assumptions about the bulge light profile are valid for his/her data.

2.7. Seeing corrections

If the user requests, *DiskFit* will blur the model, by convolving it with a point spread function, before comparing it with the data, which can be done for either photometric or kinematic fits. The blurring function is a Gaussian of specified width; note that the FWHM cannot be greater than 3 pixels. The code to compute these seeing corrections had a bug in version 1.1, which has been fixed in the present release.

2.8. Smoothing penalties

In general, *DiskFit* places no restrictions on the tabulated values of radial variation of the light profile, rotation curve, bar distortion amplitudes, *etc.* We note that *DiskFit* has an option to apply a smoothing penalty

to the radial variation of these tabulated functions, if desired. Since the smoothing penalty will affect the fitted values, it should never be large, and no smoothing is recommended in most cases. However, Sellwood & Zánmar Sánchez (2010) found that when fitting for the flow velocities of a bar that was inclined by just a small angle to the projected major axis, the velocity distortions became absurdly large and variable, and some smoothing was necessary to obtain meaningful fits.

3. OBTAINING *DiskFit*

The code is available from <http://www.physics.rutgers.edu/~spekkens/diskfit>. This website includes links to a comprehensive manual, giving full details of the procedure to use the code, data requirements, and illustrative examples, software update history, as well as executables and the source code. Versions 1.0 and 1.1 were released previously, in September 2012 and May 2013 respectively, and this posting is to announce version 1.2. The improvements at this version are that arrays are dimensioned dynamically, so that there are

no software limits to the size of the dataset that can be fitted, and several bugs have been fixed.

The authors encourage feedback from users, and will make every effort to correct bugs and inconsistencies. Requests for additional capabilities will be considered and may be provided in future releases, but the authors cannot undertake to meet every possible request.

4. COPYRIGHT AND LICENSE ISSUES

DiskFit is free software and comes with ABSOLUTELY NO WARRANTY. It is distributed under the GNU General Public License.² This implies that the software may be freely copied and distributed. It may also be modified as desired, and the modified versions distributed as long as any changes made to the original code are indicated prominently and the original copyright and no-warranty notices are left intact. Please read the General Public License for more details.

Note that the authors retain the copyright to the code and documentation. Those publishing papers that use the code are requested to acknowledge this arXiv posting as the source.

REFERENCES

- Barnes, E. I. & Sellwood, J. A. 2003, *AJ*, **125**, 1164
 Begeman, K. G. 1987, Ph.D. thesis, University of Groningen
 Kuzio de Naray, R., Arsenault, C. A., Spekkens, K., Sellwood, J. A., McDonald, M., Simon, J. & Teuben, P. 2012, *MNRAS*, **427**, 2523
 Peng, C. Y., Ho, L. C., Impey, C. D. & Rix, H-W. 2010, *AJ*, **139**, 2079
 Reese, A., Williams, T. B., Sellwood, J. A., Barnes, E. I. & Powell, B. A. 2007, *AJ*, **133**, 2846
 Schoenmakers, R. H. M., Franx, M., & de Zeeuw, P. T. 1997, *MNRAS*, **292**, 349
 Sellwood, J. A. & Zánmar Sánchez, R. 2010, *MNRAS*, **404**, 1733
 Spekkens, K. & Sellwood, J. A. 2007, *ApJ*, **664**, 204

² see <http://www.gnu.org/copyleft/gpl.html>